Scientific Basis for Requiring Flow Control at Development Sites to Protect Eastern Washington Streams

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Provided by

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1.0 Executive Summary

Water quality and stream channel degradation resulting from urbanization and increased impervious surfaces have been thoroughly documented over the years. When urbanization and development replace farm and forest land with impervious surfaces (roads, parking lots, and rooftops), the rainfall runoff volume increases. Surfaces that were previously able to infiltrate and slow runoff now quickly convey the runoff as stormwater.

Natural soil structure on land that is not transformed into impervious surfaces is lost during urbanization due to activities such as vegetation clearing and heavy equipment grading. These activities can cause soil compaction near the surface of a soil. When compaction occurs, the soil loses its ability to infiltrate, hold, and slow rainfall runoff. Development can also reduce the length of small natural drainage patterns. To make channels fit infrastructure plans, they are often ditched in straight lines or conveyed in pipes. This activity rapidly delivers rainfall runoff to receiving stream channels. The combination of reduced soil infiltration, shortened drainage patterns, and increased impervious surface areas increases the volume and speed that rainfall runs off the land. The science of analyzing and estimating the speed and volume of rainfall runoff from a watershed is referred to as hydrology. In small watersheds, changes in hydrologic characteristics resulting from development impacts can be rapid and dramatic. To understand how this can change stream channels in Eastern Washington, one must understand how hydrologic characteristics of a watershed influence the natural stream channels.

Flowing water in a watershed erodes surfaces and transports sediment. If stream energy is increased by, for instance, shortening its length or increasing flow, it will apply the surplus energy to the boundary material around the stream, causing it to erode (degrade). If stream energy becomes decreased, its ability to transport sediments is reduced, causing it to deposit sediments (aggrade). Stream channels that are considered stable are able to transport sediment through the channel with no net increase in deposition or bank erosion. However, when the hydrology of a watershed changes, the ability to transport and erode sediment changes. In some watersheds, irrigation withdrawals have caused downstream channels to fill in with sediment and vegetation. In these cases, the diversions reduced the energy needed to transport sediment loads and maintain the historic channel dimensions, so aggrading ensued. Conversely, inter-basin water transfer for irrigation or hydropower diverts flow from one channel to another. The receiving channels of these diversions then experience increased flow and energy, which results in erosion and down-cutting. Both are examples of a change in hydrology that results in a change in energy and ability to transport sediment. In both cases the channel shape or morphology adjusts to the change in hydrology.

The changing response of streams and rivers to the watershed hydrology is common to all streams and rivers around the world. Hydrology or the rainfall-runoff relationship is one of the basic independent variables that influence stream or river shape. We refer to dependent variables as a stream channel's width, depth, slope or velocity. In other words the width, slope, or depth of a stream channel depends on the overriding independent variables such as hydrology and boundary materials (bank, bed, and floodplain composition) of a stream.

Urbanization increases both the volume of runoff and the speed with which it reaches the streams. Increased runoff is an independent change in watershed hydrology that has a direct influence on the shape or morphology of a stream channel. When the volume and speed of runoff increases, a stream's sediment transport capacity increases, as well as the frequency of erosive flows, so more sediment is transported more frequently. If rapid changes in hydrology exceed a channel's ability to gradually accommodate these changes, significant instabilities in channel morphology can occur. Incision and expansion are examples of channel adjustments that follow changes in watershed hydrology that increase runoff. Unstable channels typically show active lateral migration and/or active down-cutting. Studies have shown that watershed development beyond the threshold of 10 percent imperviousness has consistently led to increased bank erosion and vertical channel instability.

Channel incision and expansion result in several negative impacts to stream ecology and biology. An incised channel generally has a simple, uniform bedform with much less complexity than existed previously. This condition leads to fewer habitats and less attractive living space for aquatic animals and insects. The ecology of the stream channel then tends to shift towards aquatic species that are more resilient, colonizing species. Research has shown a loss in fish species diversity with only highly tolerant species remaining in urban areas in watersheds with impervious areas at or near 10 percent.

The published literature reviewed in producing this white paper clearly states the need for flow control standards in urban stream channels to prevent geomorphic instability and ecological disturbance. How those standards are determined and achieved is dependent on local stream conditions and climate. Channel responses to changes in watershed hydrology are universally understood. Watershed hydrology is a significant independent variable that influences channel shape and morphology, and character of the aquatic organisms in stream channels. Boundary materials that make up the bed and banks of a stream are also independent variables and have a role to play in determining how much change can occur in watershed hydrology before a channel response occurs. Regardless of where the watershed is located in the world, these independent variables will determine the impacts to the stream morphology and the organisms dependent on that morphology. Development and urbanization change watershed hydrology by increasing peak flows. Impacts due to these changes have been published and are presented in this white paper. Although no research was found specifically regarding flow control for Eastern Washington, the need for control to protect existing stream morphology and aquatic biology is recommended. These conclusions are based on published research regarding impacts to stream channels resulting from urbanization, as well as basic fluvial geomorphic principles applicable around the world, regardless of climatic setting.

2.0 Introduction

In February 2003, Inter-Fluve was contracted by Tetra-Tech to prepare a white paper describing the effects of urban storm flows on the physical and biological characteristics of natural stream channels. This document will support the subcommittee of the Eastern Washington Stormwater Project that is developing the *Stormwater Management Manual* for *Eastern Washington* by collecting and summarizing current information describing urban storm flow impacts in semi-arid environments that exist in Eastern Washington. The goal of this paper is to provide the committee with additional information to assist in making decisions regarding flow control standards that can be implemented by local municipalities in Eastern Washington. The objectives of this paper include the following:

- Identify whether a flow control standard is needed for new development and redevelopment projects in Eastern Washington to protect biological functions in stream channels receiving discharges from those projects.
- Identify and recommend options available for establishing a flow control standard or set of standards based on regional variation or stream channel variations
- Explain the pros and cons for using any flow control classifications that are identified and recommended.
- Review existing draft Core Element #6 regarding flow control in the first draft *Stormwater Management Manual for Eastern Washington* and recommend changes or additions, if appropriate, for flow control objectives for new development and redevelopment in eastern Washington.

This paper will briefly discuss water quality and hydrologic impacts related to urban storm flow, and will focus on the geomorphic impacts that result from changes in hydrology and how those changes affect biologic functions in stream channels. Finally, this paper will review potential standards and options that are provided in the literature. The information described in this paper is based on a comprehensive, but not exhaustive, review of literature and professional contacts.

3.0 Water Quality

Water quality degradation resulting from urbanization and increased impervious surfaces has been thoroughly documented over the years. Urbanization is known generally to increase chemical and thermal pollution, increase the frequency and intensity of peak flood events, and reduce baseflow volume. Research has shown that when impervious surface cover reaches a threshold value, water quality degrades dramatically. Booth (1991) and Klien (1979) found that when watershed imperviousness reaches 12% water quality begins to degrade and becomes severely degraded when impervious surfaces reach 30%.

Increased urban land use results in an increase in nutrient loading to streams. This increase in phosphorous and nitrogen can greatly disturb the ecology of the stream environment. Organic pollution such as pet waste, lawn clippings and litter can build up in streams and their decay often results in reduced oxygen levels. The levels of bacteria, including fecal coliforms, in urban runoff often exceed public health standards for swimming and wading. Toxic chemicals such as insecticides, herbicides, hydrocarbons, polychlorinated biphenyls (PCBs) and Heavy metals such as lead and zinc are common contaminants in urban waterways.

Thermal impacts to water quality can result from modification to riparian buffers and is a direct result of runoff from previously heated impervious surfaces such as parking lots. Galli (1990) completed an extensive report on thermal impacts associated with storm water. He found that when air temperatures remained at or above 80 degrees Fahrenheit for long periods of time heavy shower activity could increase stream temperatures. The same storms that cooled stream temperatures in undeveloped watersheds increased stream temperatures in developed watersheds as the amount of heated water running off streets or parking lots increased.

4.0 Stream Hydrology

Urban growth influences the timing and volume of runoff to receiving streams in a variety of ways. The primary influence of urbanization on hydrology is due to impervious surfaces that change the runoff characteristics of urban streams. These influences were summarized by Hajda et al. (1999):

- The increase in impervious surfaces slows or eliminates the chance for water to infiltrate into shallow ground water aquifers that would slow runoff during storms and provide base flow later in the year.
- Impervious surfaces are generally much smoother surfaces than natural ground cover and as a result water runs across them much faster. This increases the volume of surface contribution.
- Because surface flow is moving faster, the time of concentration or delay of water making it into a stream channel is much less. This creates a compressed hydrograph with a greater peak flow and more rapid rise and fall on either end.

The magnitude and frequency of all stream flood events increase with increasing imperviousness. This is especially the case for smaller runoff events or rainfalls of smaller magnitudes. Prior to development, most of the precipitation from small events infiltrates and runoff is correspondingly low. Following development and increase in impervious surface cover, the same precipitation events do not infiltrate as much and result in more frequent, intense surface runoff.

Many studies have documented the influences of man-made impervious surfaces on watershed hydrology. Burges et al. (1998) found that the peak flow rate per unit area was more than 10 times higher from suburban areas than adjacent forested areas. Hollis (1975) found that floods with return periods of a year or longer are not changed by up to 5% impervious area, but that as impervious area grows small floods can increase by a factor of 10. In addition, 100-year floods can be doubled in size as impervious areas approach 30%. Impervious surfaces have substantial impacts within watersheds where subsurface flow dominates under natural conditions (Booth 1991). The reduction of infiltration due to increased imperviousness can influence the volume of base flows. The degree of base flow reduction is dependent on watershed characteristics and degree of urbanization. Schueler (1994) summarized that the impacts of reduced infiltration on base flow can be quite variable. However, a recent study (Finkenbine et al. 2001) found that summer base flow was "extremely low" when impervious area increased to more than 20% to 40%. When imperviousness is less than 20%, base flow impacts can vary due to variability in local geology and climate, but as impervious area increases, base flow impacts become much more evident. This threshold value of impervious cover is different for all watersheds. Watersheds in arid climates that are dependent on surface water base flow are generally more vulnerable to base flow changes than watersheds in humid climates due to the limited volume of ground water available for release at dry times of the year in arid climates.

5.0 Geomorphic Stability

Impacts to the physical form and function of stream channels resulting from impervious area have been well documented. Many studies have been completed that studied hydrologic changes to receiving urban streams and the resulting fluvial geomorphic response. Wolman (1967), Graf (1975) and Hollis (1976) found that the most prevalent response following land development is an increase in fine sediment supply to stream channels from land clearing and construction. This trend continues until build out and is eventually followed by a reduction in sediment supply, particularly course materials. Increases in peak flow events combine to increase sediment transport capacity in urban channels. This increase in sediment transport capacity lowers the threshold and frequency of when bank and bed material can be moved. This changing threshold is often a precursor to channel instability.

The threshold at which bed material moves is called the threshold of *incipient motion*, and is dependent on the *critical shear stress*, or the force of the moving water on the stream substrate. The critical shear stress is affected by the stream discharge, channel shape and the size of natural sediment load moving through the stream channel. As discussed above, urbanization directly affects both the stream discharge and sediment supply components of this relationship. With further definition, the stream discharge that moves the most amount of sediment over time is referred to as the *effective discharge*.

The effective discharge and its relationship with local geology have the greatest influence on the shape of the channel over time. This relationship results in channel adjustments following a 1.5 to 5-year return interval frequency for many streams (Leopold 1964). In other words, the geology surrounding the stream channel is typically erodeable or moldable during floods that on average occur every 1.5-5 years. Increasing impervious area in a watershed essentially changes the relationship between the frequency of flood events and the ability of the local geology to withstand those changes. The result of these changes is evidenced by increased erosion and channel instability during floods that occur very frequently, often annually or several times a year.

Human efforts in responding to increased frequency of channel changes include stream bed and bank armoring (in effect changing local geology) or efforts to control floods. Unfortunately, flood control measures which addresses flow rate alone often result in controlled discharges at that flow rate being released for longer durations (needed to pass the increased runoff volume) than the channel experienced before development. The increased duration of these events results in substantially more energy being delivered to an urbanizing stream channel over time.

Unstable channels typically show active lateral migration, active downcutting or both. Watershed development beyond the threshold of 10% imperviousness has consistently led to increased bank erosion and vertical channel instability (Hollis, 1975). As the channel bottom lowers, the stream becomes disconnected from its floodplain, and runoff events that would normally have dissipated their energy across the floodplain surface are now confined to the enlarged channel. This downcutting increases the erosive power of the stream, speeds the runoff velocity and reduces runoff retention that could occur on the floodplains. The elevated erosive power increases the movement of sediment from bed and banks, often resulting in channel incision, expansion and destabilization in upstream reaches. This vertical instability causes downstream deposition, loss in channel capacity, flooding and lateral instability (Doyle et al. 2000). Eventually, a new equilibrium develops and at this stage most streams have less fine sediment in them than before development (Finkenbine et al. 2000). Arnold (1982) observed a similar cause and effect through an increase in the frequency of the smaller bankfull discharge. In his study he found that increased flood flows from impervious areas destabilized stream banks and increased the size of the bedload discharge. This material deposited downstream in the form of mid-channel bars that further destabilized stream banks creating a braided unstable channel.

Several researchers have shown that instability in urban channels is variable and affected by a variety of factors. For example, bank widening and erosion can substantially increase following incision, but in some cases, bank widening doesn't occur. Harvey (1986) states the degree of bank stability following incision depends on the bank height and the geotechnical properties of the bank material. For example, clay would be much more resilient than sand and gravel following incision. Hammer (1972) found that the influence of the channel slope and topography of the land development itself played a large role in channel stability. Further he stated that the level of storm sewer development in roads was important, as roads with extensive storm sewer catchments played a larger role in channel instability than those that did not because of the rapid delivery of storm flow to stream channels. Bledsoe (2001) found impermeable surface increases of 10-20 percent have great potential to increase stream peak flows and stream power. However, potential destabilization associated with increased impervious area can be highly variable and depend on watershed-specific conditions.

6.0 Biotic response

In most urban situations, a combination of all of the aforementioned factors contributes to loss of ecological function. Indeed, many water quality assessments conclude overall loss of biological function rather than simply attempting to pinpoint individual causes. In the paragraphs below, likely ecological impacts are outlined as a response to a variety of impacts, unless specific causes are noted such as thermal pollution or hydrologic change.

6.1 Water quality impacts to aquatic biota

Water quality impacts to aquatic species have been well documented; although it is often difficult to discern which urban land use factors are causing specific effects. A large percentage of toxic chemicals that enter stream channels do so after collecting on impervious surfaces during dry periods and are then directly washed into streams following storm events. Various researchers have found major changes in the macroinvertebrate communities in urbanizing stream channels, indicating a distinct response to pollution and reduced water quality (Hachmoller et al. 1991, Jones and Clark 1987). High levels of toxicity during storm events have been found by Medeiros et al (1983) to reduce aquatic species diversity and richness.

Fish populations in urban areas tend to mimic macroinvertebrate population trends of low abundance and diversity (Weaver et al. 1994, and Talmage et al. 1999). A study of 34 sites (Poff et al. 1995) showed that hydrologic changes either due to "climate change or other anthropogenic disturbances could modify stream fish assemblage structure". Development and riparian loss even at low levels can impact warm and coldwater fish assemblages similar to that in high intensity perturbations, often shifting the community from a high diversity of pollution intolerant species to a community characterized by a low diversity of pollution tolerant species.

6.2 Thermal pollution effects on the biota

Stream temperature increases can have more significant effects in cold-water stream channels (Galli 1990). The reduction in ground water flows, removal of riparian vegetation and drainage network alteration can contribute to thermal loading in urban areas. Protecting mature riparian buffers are one way to reduce the extent of thermal loading in cold-water streams. Engineered storm flow infiltration mechanisms that slow and/or filter direct input from impervious areas into the stream channel also aid water quality treatment related to water temperature and toxic chemicals.

Coldwater fish species are vulnerable to sudden changes in stream temperature known as heat shock (Becker 1973). The potential to rapidly increase stream temperature and impact fish exists in Eastern Washington from summer thunderstorm runoff across heated impervious surfaces. The rate of temperature rise in receiving streams can be reduced through detention. Detention helps by delaying and slowing the thermal load and temperature rise in receiving streams.

6.3 Hydrologic and geomorphic effects on the biota

Channel incision and expansion have several negative consequences to stream ecology and biology. An incised channel generally has simple bedforms with much less complexity than existed previously. This condition leads to fewer habitats and less attractive living space. Imagine a house with only one room and no furniture verses complex habitat that has many rooms filled with living conveniences. The ecology of the stream channel then tends to shift towards aquatic species that are more resilient colonizing species. Scott (1986) found that development has resulted in a less diverse fish community than that which existed before development. More tolerant cutthroat trout populations exist today and fewer species of sculpin and coho exist due to increased bed scour from peak flows and elevated sediment from new development activities within the watersheds studied. Other research has shown a similar loss in fish species diversity with only highly tolerant species remaining in urban areas with impervious area of watersheds at or near 10 percent (Wang et al. 2001). Wang speculates the loss in fish species diversity was primarily caused by more frequent larger floods and reduced base flow following development and increases in impervious area.

6.4 Other effects on the biota

Degraded riparian areas were identified in the research as a consistent factor behind the reduction in fish habitat. Riparian areas can be degraded by both the physical removal of buffers for development and the loss of trees from channel incision, expansion and erosion. In areas with very thin buffers the loss of trees can degrade water quality through increased stream temperatures in the summer. May et al. (1997) found that the loss of large wood material generated from healthy riparian areas significantly reduced habitat in stream channels in urban stream channels.

7.0 Flow Control Standards for Urban Channels

The published literature reviewed for this white paper clearly shows the need for flow control standards in urban stream channels to prevent geomorphic instability and ecological disturbance. How those standards are determined and achieved is dependent on local stream conditions and climate. This section describes three different approaches that relate flow control standards to stream stability and ultimately aquatic stream health. They are referred to as (1) *channel threshold discharge*, (2) *watershed based zoning* and (3) *range of variability* approaches.

7.1 Channel Threshold Discharge

One method proposed by Booth (1997) states that maintaining the stability of a stream channel can be achieved by understanding what discharge begins to mobilize bed and bank sediment. As previously discussed, the *effective discharge* is the discharge that moves the most stream channel sediment over time. Booth's method assumes that if the post-development discharge is kept below the effective discharge threshold, the stream channel will remain stable and the aquatic biology will remain healthy. The effective discharge is often close to the 1.5-year discharge (annual flood series) that has been commonly referred to as the bankfull discharge by many (Leopold 1964). Although the median bankfull discharge is often described as the 1.5-year discharge, research has shown that there are a small percentage of streams that do not share this relationship (Williams 1978).

Booth and Jackson (1997) summarized the published research and found that between 14 and 90 percent of the streams studied achieved sediment mobility thresholds during the 2-year discharge (the 1.5-year discharge falls within this range). Instead of matching peak discharges as has been historically implemented, the idea of releasing the 2-year post-development runoff volume at 50% of the pre-development 2-year discharge was proposed as a way to mitigate for the increased duration of the effective discharge in urbanizing streams. This is the standard that was chosen for Western Washington streams (1992) and is also the draft standard for Eastern Washington streams. The argument for a single threshold discharge value can be made because it is easily applied to many different stream channels. The disadvantage is that by taking an average value one can miss on either end of the spectrum. The best relationship probably varies as much as local geology that can be quite variable in systems with both natural geology and human imposed geologic features.

7.2 Watershed Based Zoning

A watershed based zoning approach to determine flow control standards was proposed by Schueler (1994). This method takes a more involved field level approach that lends itself well to long range growth planning. This approach utilizes the documented relationship between watershed imperviousness and stream quality. Schuler provided a classification between impervious cover and stream health as follows:

- Stressed streams (1 to 10% imperviousness)
- Impacted streams (11 to 25% imperviousness)
- Degraded streams (26 to 100% imperviousness)

Streams in developed and currently developing areas are classified depending on the percent imperviousness within each watershed. Classifying the streams provides a pragmatic framework to manage streams based on current and future growth. Stressed streams would have the strictest enforcement of buffers, retention/detention facilities and water quality parameters to maintain existing hydrologic conditions and water quality. Impacted streams would be expected to have some level of degradation and the goal would be to limit the level of degradation and loss in bio-diversity. The degraded streams have high levels of imperviousness and stream degradation already. In these streams, the focus would be on water quality and, where possible, restoration activities that would begin to provide improved conditions for a greater degree of species diversity.

Once the imperviousness within each watershed has been determined and the stream classified, a watershed based zoning effort can be implemented. The effort is completed in four steps. The first step completes a *physical, chemical and biological monitoring* effort to determine existing conditions within each stream. This provides an understanding of the condition of each stream compared to existing imperviousness and the potential resiliency of the streams following future growth. The second step *maps imperviousness* as it occurs at the sub watershed level. Future growth projections and imperviousness are also made at the sub watershed level. The third step *designates future stream quality* for each stream based on the imperviousness stream classification. With this information completed, the jurisdiction would have an existing conditions classification of streams based on imperviousness and a build-out classification of the same streams. Based on this information the master plan can then be revised to be consistent with the degree of imperviousness and stream quality goals for each stream.

The final step determines more *specific resource objectives* for each stream and sub watershed. At this stage specific polices or ways to achieve success within each classification are provided. BMPs, buffers, retention facilities and other practices are outlined for future development projects from knowledge gained from the assessment process.

Watershed-based zoning takes a more detailed look at existing physical condition and biology within urbanizing watersheds and can provide a way to make more informed natural resources planning decisions. Watershed-based zoning allows cities and counties to make better choices regarding urban stream channels. For example if one watershed and stream are already degraded due to imperviousness and another in good condition, this technique would allow the jurisdiction to make an informed decision to adjust its growth plans to retain the quality of a stream channel at the expense of one that is already degraded. This method of mitigation may be seen as disadvantageous by a regulatory official who cannot legally permit further degradation of water quality. This method is also more expensive due to the field work required in the initial stream channel assessments.

7.3 Range of Variability Approach

A third method to determine flow control standards is called the Range of Variability Approach (RVA) proposed by Richter et al. (1996, 1997, and 1998). This method bases flow control requirements on a comprehensive statistical characterization of flows most important to ecologic process existing in streams and rivers. A management system is established that will attain a group of target flows and durations throughout the year that maintains stream stability and ecological integrity. The following groups are provided to show the level of detail the flow targets are based on:

- Magnitude and monthly water conditions;
- Magnitude and duration of annual extreme water conditions;
- Timing of annual extreme water conditions;
- Frequency and duration of high/low pulses; and
- Rate/frequency of water condition changes.

These five groups include 32 ecologically relevant hydrologic parameters. These are called Indicators of Hydrologic Alteration (IHA). Each one of these parameters can be obtained from existing streamflow gauge data for a period of record greater than 20 years.

Once these data are collected, the hydrologic characteristics must be determined for pre-existing conditions within the watershed. All of the relevant flow data in each group is analyzed for central tendency (mean, median) and dispersion (range, standard deviation) from the annual series for each of the 32 parameters within the five general groups. Half of the parameters focus on magnitude, duration and frequency of extreme events. The other half describes the central tendency of either the magnitude or the rate of change within each condition. These data provide a detailed summary of the magnitude and frequency of discharges important to stream stability and ecological diversity.

The second step develops a range of natural variation around each of the 32 parameters as defined by the dispersion around them. This range becomes the management target for that stream channel. The team responsible for the flow target must determine the range or dispersion around the target. This is based on ecological information within the region. These finalized target discharges are called the RVA target flows.

Once the targets are established, management agreements/standards to achieve the targets are developed. At this time, a monitoring program is implemented to assess the ecological effects of the new RVA target flows on the stream channels. As new information is gained or research is competed, the target flows may be adaptively adjusted.

RVA is a very robust way to look at pre-existing hydrologic conditions and how those conditions change due to land management. The applicability of RVA to some urban stream channels may be limited because many streams have no streamflow gauge data.

This can be overcome using gage data on adjacent streams with similar climate and geology or at a higher cost by developing hydrologic simulation models of the watersheds in question. Richter states that the specific hydrologic data for the target discharge relating to ecologic health has not been statistically proven with any rigor. However, the premise of this approach is a logical way to determine an understanding of the connection between biology and hydrology. It is assumed that geomorphic channel adjustments and process will be stable if the RVA targets are followed in this method. This method would be the most expensive approach of the three and would require an adaptive management approach for storm water control over time.

8.0 Conclusions

The following conclusions and recommendations address the questions presented by the Manual Subcommittee regarding storm flow controls in Eastern Washington.

8.1 The Need for Storm Water Control

The literature review found no previous research for flow control in urban channels in Eastern Washington and very limited research in semi-arid environments in general. This was confirmed as a void in the published research by Schueler (1994), Booth et al. (1997) and personal communication with Barber (2003), Brown (2003), McCoy (2003) and Moran (2003). In addition, the differences between the hydrology and geology of semi-arid streams and those in humid environments, where research has been completed, are significant. However, the physical processes that drive stream channels are the same regardless of location and climatic setting.

The frequency and timing of runoff characteristics shape the physical morphology of a stream and in part determine the composition and health of aquatic communities. Hydrologic changes can be expected to have consequences to stream stability and process. The specific impacts of changing hydrologic regimes for Eastern Washington streams are not well studied and warrant further investigation.

Although the level of regional detail between hydrologic and biological interactions is not fully understood, what is clearly documented and well-understood is the reduction of species diversity and richness that follows hydrologic modifications and subsequent morphological changes in stream channel stability, shape and function. Water quality also plays a large role in the health of aquatic communities and, without it, biologic function cannot exist at the level previously found – regardless of the physical habitat. Existing aquatic species adapt much more slowly than the rate of physical change caused by increasing urbanization. These adverse impacts have been documented in the research and suggest a similar trend for semi-arid streams such as those in Eastern Washington.

Although no research has been completed for Eastern Washington regarding flow control, the volume of literature found on the subject indicates there is a need for a flow control standard to protect the physical stability and biota of urban stream channels in Eastern Washington.

8.2 Flow Control Standards

Three options for the development of flow control standards were presented. They are:

- Channel threshold discharge provided by Booth (1997).
- Watershed based zoning method developed by Schueler (1994).
- Range of variability approach suggested by Richter (1998).

8.2.1 Threshold Discharge

The greatest advantage to using the channel threshold discharge method of releasing the post-developed 2-year runoff volume at 50% of the two-year pre-development discharge is the ease of application. It is a distinct target that can be applied across a variety of channels. It is based on a variety of studies that indicate channel stability is closely related to the discharge that begins to mobilize channel sediment. This discharge varied between 14% and 90% of the 2-year discharge.

The disadvantage of this method is the variability on either end of the spectrum. Channels that would move sediment at 14% of the 2-year discharge could become unstable at 50% of the two-year discharge. The use of this discharge target in the draft Eastern Washington Stormwater Manual is defendable and is based on existing research. It is recommended that if this number is used it be adapted as more information becomes available for Eastern Washington streams. In Eastern Washington, regional storm variation and, more importantly, the variety of stream channel geology may provide a basis for adjusting flow control thresholds that make them either more or less restrictive. Further study would determine if these adjustments are best made on a regional or watershed scale.

8.2.2 Watershed-Based Zoning

Watershed-based zoning suggested by Schueler takes a more physical and biological analysis of existing conditions compared to impervious area within urban channels. By doing so it provides the ability to understand what is or has occurred within stream channels and then applies that knowledge to future growth and management within the watershed. Watershed-based zoning provides a greater degree of assurance that protection of physical and biological habitat will occur by developing standards for protection based on individual watersheds and collected data. The disadvantage to this method is the level of interpretation needed to determine existing conditions and recommendations to protect urban stream channels. As a result this method is more lengthy and expensive than a single flow control standard.

8.2.3 Range of Variability

The range of variability approach (RVA) is an intensive analysis of existing or modeled flow data. The premise behind this method is that by emulating hydrologic attributes of pre-developed stream channels, the post-developed streams will be physically and ecologically stable. The level of detail in the RVA makes it more suitable for minimizing hydrologic impacts to physical and ecologic stream processes than any other method.

The RVA is data intensive and requires a team approach to agree on the range of flow variability allowed to maintain physical and biological stability in given stream channels. The RVA requires a certain level of interpretation, making it more time consuming and expensive than a single flow standard.

8.3 Flow Standard Recommendation

The lack of research relating to stability and development in Eastern Washington shows the need to encourage research projects that study impervious surface impacts to stream channels in Eastern Washington. Review of literature has shown two general approaches to flow control: 1) determining a single flow standard for an area and; 2) determining more specific standards based on individual channels.

Because of the lack of data for Eastern Washington, use of the 50% of the 2-year discharge standard to protect stream channels in Eastern Washington may be appropriate. It is suspected that given the geology and terrain, there is a greater degree of stream channel variability in urbanizing streams of Eastern Washington than in urbanizing streams in other regions. Based on this assumption, it is highly recommended that fluvial geomorphic and hydraulic analysis be used to examine effective discharge of Eastern Washington stream channels as they relate to the 50% of the 2-year discharge standard. Studies that examine these issues should provide a better understanding of the discharge/stability relationships that exist in urbanizing streams of Eastern Washington. Following these studies it may be appropriate to adjust the flow control standard. Whether these adjustments would occur on a watershed or regional scale is difficult to predict.

An adaptive management process that provides a framework for local communities to adjust flow control requirements, as more information is made available seems appropriate. Studies that first establish an understanding of local or regional stream channel stability risk should be completed based on physical stream data and hydraulics. The study completed by Cappuccitti (2000) comparing boundary shear with critical shear of measured bed material and channel dimensions is a good example. These studies would provide the bases for a proposed adjustment in the previously established flow control standard. The scale of the study would determine the area adjustment in flow control allowable by regulatory agencies.

9.0 Flow Control Standard (Core Element #6 of the *Stormwater Management Manual for Eastern Washington*)

The *Draft Stormwater Management Manual's Core Element #6: Flow Control* was reviewed to determine consistency with existing research. The objectives, guidelines and intent of this section are consistent with what was found in the literature. The major unresolved questions in Core Element #6 are: 1) what is the proper design storm to use in setting the target flow rate, and 2) what Eastern Washington streams should be subject to the flow control requirement? The first problem stems from the different types of storms that have an influence over discharge events in Eastern Washington (intense summer thunderstorms versus extended, low-intensity rainstorms in winter/spring; and snowmelt events). No research was found regarding stable stream flow control in semi-arid climates that would help answer these questions. To provide some guidance and recommendations, runoff characteristics and general geomorphic stability will be discussed. This will be followed by recommendations regarding watershed (stream size) to be concerned with and precipitation regime to use in designing flow control facilities.

9.1 Runoff Characteristics

Runoff characteristics on the east and west sides of the Cascade Mountains are fundamentally different. On the west side of the Cascades, storm flow runoff is more likely to be slow because of the vegetation, soil infiltration capacity and low precipitation intensities. On the east side, intense precipitation falls on soil surfaces that cannot absorb the rainfall, resulting in overland flow. This is often referred to as Horton Overland Flow (Horton 1945). Poorly developed shallow soils that cannot support substantial vegetation are most susceptible to overland flow. This type of condition is much more common in semi-arid environments in Eastern Washington. Shallow, less developed soils with sparse vegetation can become overwhelmed during high intensity storms, resulting in rapid rainfall runoff characteristics.

In arid climates, existing stream channels have developed with more natural runoff than streams in humid areas. As a result, in semi-arid areas stream channels may be more resilient to increases in impervious area because of this previous adaptation. Therefore, the impervious area threshold for stream channel degradation may be higher in areas with more natural overland flow than those with more subsurface flow as occurs on the west side of the Cascades. This would increase the amount of imperviousness that could be created in a watershed without resulting in channel instability and may reduce the need for flow control in those streams. This is a basic research question that should be studied. A more conservative approach should be taken until this question is answered regionally or on a watershed-specific basis.

This generalization fails to take into account areas of Eastern Washington where infiltration rates are naturally high. In these areas, imperviousness would rapidly increase effective flows acting on the stream channel following development. Therefore, depending on the natural watershed infiltration rates, the effects of imperviousness could be highly variable. Existing information is lacking regarding infiltration rates within sub-watersheds and how those rates relate to peak flows and the risk of channel stability in Eastern Washington streams.

9.2 Geomorphic Resiliency

Sediment transport in urbanizing streams is directly affected by increased timing and volume of runoff. To predict the success of a flow control standard, the relationship between sediment transport and control measures for stable thresholds must be understood.

To determine effectiveness of different flow control protection methods, Cappuccitti et al. (2000) looked at the ratio of average boundary shear stress found by cross section analysis to critical shear stress of the sediment in the channel. Vulnerability within stream reaches was highly variable in the piedmont region of Maryland. This variability with respect to evaluating the effectiveness of storm water control shows the need for further research in this area and the value of understanding existing channel stability and risk of instability within developing watersheds. A channel can be considered stable when the shear stress ratio is below 1.2. A shear stress ratio greater than 2.5 indicates channel instability, and ratios between 1.2 and 2.5 are transitional: both degradation and aggradation can occur depending on sediment being supplied to the channel (Prestegaard 2000, Johnson et al. 1999).

Many streams are laterally resistant to erosion following incision caused by urbanization. This erosion resistance is due to the cohesiveness of clay bank soils. Channels that are composed of silt, sand and alluvial gravel have a greater potential to erode than do clay banks; these types of channels would also be most vulnerable in Eastern Washington.

Topography plays a key role in channel stability: the steeper the channel slope and development site, the greater risk for instability. Existing riparian health is also important to consider when maintaining channel stability.

9.3 Watershed size

Research has shown that smaller channels ranging in size from 1st through 3rd order streams are most easily impacted by development. These smaller watersheds are vulnerable because any change in land use and development rapidly increases watershed impervious area compared to the size of the watershed. Alternatively, large streams and rivers are not impacted as heavily by imperviousness because any increase in hydrology is very small compared to the effective discharge that created and maintains the channel shape. This does not, however, preclude the need to maintain water quality in all streams large and small.

9.3.1 Recommendation

Therefore, the developments that discharge into larger rivers will not impact the physical processes occurring. Where this cutoff exists east of the Cascades may vary on annual precipitation. No research was found that would provide guidance on the size of stream that could be waived from flow control in Eastern Washington. Research completed in Maryland has found this cutoff normally occurs around a 4th order channel. The easiest way to determine which streams should be waived is to examine impervious area compared to watershed size. Research has shown that less than 5% impervious area has minimal impact on stream stability. In the absence of compiling this information, it is recommended that 5th and greater order streams are exempt from flow control requirements on an interim basis until more is known about Eastern Washington streams.

9.4 Precipitation Regime

For smaller watersheds, short-duration, high intensity thunderstorms can produce flash flooding over smaller watersheds. Although the floods can be quite high, they are generally of short duration. In some cases, these events can produce debris torrents in steeper drainages that have the potential to mobilize large volumes of soil and substrate out onto alluvial fans. These events are rare but they do exist.

On a more frequent basis, thunderstorm-generated floods occur because the rate of precipitation is so much greater than the soil infiltration rates. In this respect the difference in runoff from pre-development to post-development would be similar since the rate of precipitation is high. In either case runoff is high. Short duration intense storms come and go quickly. As a result the energy on the channel, although intense, does not have the duration to complete a large amount of work.

Alternatively, long duration storms that occur with less intensity but longer periods of time can have a greater potential to change channel shape since the peak discharge duration is high for a longer period of time. Following development, more flow is delivered to the receiving streams over a longer duration. Storms that would normally have some infiltration have more water delivered to the channel more frequently and for longer durations.

9.4.1 Recommendation

Precipitation events that produce effective flows of the greatest duration before development are the types of event driven discharges flow control should be targeting to maintain channel stability and biological health. Duration is a significant factor in determining how much sediment transport occurs once flows capable of moving stream sediment are reached.

Summer thunderstorms are short duration high intensity events. Precipitation is so intense that infiltration rates of local soils in arid regions are easily overwhelmed and runoff occurs more rapidly. The long duration storm is less intense but is able to infiltrate prior to urban development. Following development this ability is diminished and more total runoff occurs. Questions regarding the ability to control both short and long duration storms have been identified. If a choice between two types of precipitation must be made, controlling the longer duration event that produces the pre-development effective flow will protect an urban channel better than controlling for a shorter duration thunderstorm. The long-duration event should be managed in a way that protects the predevelopment effective flow discharge. This approach has been identified in the Draft Eastern Washington Stormwater Manual as releasing the 2-year post-development volume at 50% of the pre-development 2-year discharge rate. The long-duration design storm should be used to identify the pre- and post-development volumes and flow rates upon which structural design of flow control facilities will be based.

9.5 Proposed exemptions for Eastern Washington

Research has shown that in general, flow control is not needed for discharges into 4th order or greater streams, in lakes, controlled reservoirs or wetlands with no outlets. Large rivers such as the Columbia and Snake would be exempt from flow control under this standard for all of Eastern Washington. Rivers of this size are not impacted by impervious area since their watersheds are so large compared to the potential level of imperviousness. Small drainages rise and fall before flood peaks and effective flows in larger rivers. The cutoff for requiring flow control in Eastern Washington should exist at the 4th or 5th order stream channel. Due to the lack of information currently available, 5th order and larger streams could reasonably be listed as exempt from flow control requirements. The maximum potential percent impervious area for the large drainage areas should be checked before a standard is set. The percent impervious area within those drainages should remain below 5% if they are allowed to remain exempt.

Discharge into irrigation return flow channels could be exempt if the capacity is adequate, stable and they do not have fish spawning and rearing habitat. There is some risk in providing an exemption due to unforeseen impacts to return flow channel stability. When storm flow generated by impervious surfaces is discharged into irrigation return channels, the irrigation channels can rapidly destabilize the same way natural channels do. Head cutting and expansion could work upstream in steeper locations causing excess sediment and degraded water quality in downstream channel segments with fish habitat and spawning areas. Deposition from upstream erosion could also result in the loss of return flow channel capacity and flooding. At a minimum these risks should be assessed as part of an exemption process regarding irrigation return flow channels.

Other existing exemptions listed in the first draft *Stormwater Management Manual for Eastern Washington* are consistent with published research. These exemptions should be monitored to determine whether any unintended damage to stream channels follows their exemption. The exemptions should be modified, as information is made available.

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